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Waste Food to Energy: Sustainable Bioenergy Conversion

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A R T I C L E I N F O

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A B S T R A C T

Food waste represents a significant fraction of global municipal solid waste and constitutes a critical environmental and economic challenge. With rising urbanization and food consumption patterns, the need for sustainable and circular solutions is paramount. This review comprehensively evaluates the potential of converting waste food into energy via various biochemical and thermochemical technologies, focusing on anaerobic digestion, gasification, pyrolysis, and direct combustion. Emphasis is placed on technological feasibility, energy efficiency, environmental impacts, and integration into existing energy frameworks. The paper also explores the barriers to commercialization, such as feedstock heterogeneity, pretreatment complexity, policy limitations, and public perception. A comparative analysis is presented to assess the scalability and techno-economic viability of different conversion methods. Ultimately, the review proposes an integrated system combining pre-sorting, microbial enhancement, and hybrid thermochemical-biochemical routes to maximize yield and minimize emissions. This work highlights the underutilized potential of food waste as a renewable energy source and outlines future research directions for optimizing waste-to-energy (WTE) solutions in alignment with global sustainability goals.

1. Introduction

Food waste is a growing global concern that intersects environmental, economic, and social dimensions. According to the Food and Agriculture Organization (FAO), approximately 1.3 billion tons of food are wasted annually, representing nearly one-third of all food produced for human consumption. This wasted biomass results not only in the loss of valuable nutrients and resources but also contributes significantly to greenhouse gas emissions, particularly methane, which is 25 times more potent than CO_2 over a 100-year period. The mismanagement of food waste exacerbates landfill overflows, releases leachate into groundwater systems, and strains municipal solid waste (MSW) infrastructure. In this context, waste-to-energy (WTE) conversion offers a viable route to valorize food waste into useful forms of energy while reducing the environmental burden.

The interest in converting waste food into energy is driven by its high biodegradability and moisture content, making it particularly suitable for anaerobic digestion and composting. In urban settings, food waste can be separated at the source and routed to decentralized digesters or centralized treatment plants for biogas production. This biogas, a mixture of methane and carbon dioxide, can be used for electricity generation, heating, or upgraded to biomethane for injection into the gas grid. Several studies have demonstrated the feasibility of co-digesting food waste with other organic residues, such as sewage sludge or agricultural biomass, to improve biogas yield and system stability. However, the process is challenged by substrate variability, the presence of inhibitory compounds, and the need for post-treatment of digestate.

Besides biochemical pathways, thermochemical technologies such as pyrolysis and gasification have emerged as alternatives, especially for treating mixed or contaminated food waste streams. These processes operate at higher temperatures in oxygen-limited environments, resulting in the production of syngas, bio-oil, and biochar. While they offer higher conversion efficiency and the ability to handle heterogeneous feedstocks, these technologies are energy-intensive and require advanced gas cleaning systems. The integration of food waste-derived syngas into fuel cells or combined heat and power (CHP) systems is an area of active research, with promising implications for distributed renewable energy generation.

Economic and policy incentives also play a crucial role in determining the adoption of food WTE solutions. In countries like Sweden and South Korea, strict landfill bans and government subsidies have led to widespread implementation of anaerobic digesters and composting facilities. Conversely, in regions with limited regulatory enforcement or high capital costs, food waste is still predominantly landfilled or incinerated without energy recovery. The challenge remains in establishing cost-effective and socially acceptable waste management systems that align with circular economy principles.

One important consideration is the energy balance and lifecycle impact of different food WTE technologies. While anaerobic digestion exhibits favorable energy ratios and low carbon footprints, its performance is sensitive to feedstock composition and process conditions. Gasification and pyrolysis, although more robust, require higher energy inputs and may emit harmful pollutants if not properly controlled. Therefore, a techno-economic and environmental assessment is essential to guide technology selection and policy frameworks.

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Nomenclature

Abbreviation
AD – Anaerobic Digestion
WTE – Waste-to-Energy
MSW – Municipal Solid Waste
CHP – Combined Heat and Power
SOFC – Solid Oxide Fuel Cell
LCA – Life Cycle Assessment
HRT – Hydraulic Retention Time
TS – Total Solids
VS – Volatile Solids

Symbol
P – Pressure (Pa)
T – Temperature (°C)
η – Efficiency (%)

2. Methodology

The methodology adopted in this review synthesizes experimental, pilot-scale, and theoretical studies related to the conversion of food waste into usable forms of energy. Peer-reviewed literature from databases such as Scopus, Web of Science, and Google Scholar were analyzed, covering the period from 2005 to 2025. Studies were selected based on relevance, citation index, experimental rigor, and geographical coverage. Conversion technologies reviewed include anaerobic digestion, gasification, pyrolysis, hydrothermal liquefaction, and direct combustion. Comparative analyses were conducted focusing on energy yield, conversion efficiency, feedstock requirements, and environmental performance. Pre-treatment methods and their impact on energy recovery efficiency were included to assess practical feasibility and techno-economic implications.

Anaerobic digestion (AD) was analyzed as a biological method that breaks down organic matter in the absence of oxygen through microbial processes. Substrates used include raw food waste, cooked leftovers, and food processing residues. Important parameters such as pH, temperature (mesophilic: 35–38°C and thermophilic: 50–55°C), total solids (TS), volatile solids (VS), and hydraulic retention time (HRT) were considered. The biogas composition (typically 50–70% CH_4 and 30–50% CO_2) and the methane yield (in m^3 CH_4 per kg VS added) served as key performance indicators. Data were extracted to compare the effects of co-digestion, organic loading rate (OLR), and inoculum types on gas production. The role of pretreatments—thermal, mechanical, enzymatic, and microwave-assisted—was also assessed to understand how they increase digestibility and accelerate hydrolysis kinetics.

Gasification methodology was investigated as a thermochemical process conducted at high temperatures (typically 700–1000°C) with controlled oxygen or steam. The review focused on air-blown, oxygen-blown, and steam-blown gasifiers, and the effect of equivalence ratio on syngas yield and tar formation. Proximate and ultimate analysis of food waste was considered essential to determine its compatibility with gasification. The energy yield was expressed in terms of syngas volume per kg of dry biomass and the calorific value (MJ/kg). Catalytic and non-catalytic gas cleaning technologies were examined, and syngas upgrading for fuel cells and synthetic fuel synthesis was also evaluated. Special attention was given to the efficiency of integrated gasifier-fuel cell systems and the role of sorbents for CO_2 removal.

Pyrolysis was reviewed with respect to its operational temperature range (300–600°C) and heating rate (slow, fast, or flash pyrolysis). The product distribution between biochar, bio-oil, and syngas was compared across multiple studies. The composition of bio-oil was analyzed for acidity, viscosity, heating value, and suitability for upgrading into transportation fuel. Reactor types included fixed-bed, fluidized-bed, and auger systems. Thermal pretreatment methods such as torrefaction and hydrothermal carbonization (HTC) were explored to improve the homogeneity and energy density of food waste feedstock. Pyrolysis char was evaluated for use in soil amendment, carbon sequestration, and electrode materials.

The hydrothermal liquefaction (HTL) methodology was reviewed for its ability to convert high-moisture food waste into biocrude under subcritical water conditions (typically 280–370°C, 10–25 MPa). Process parameters such as reaction time, feedstock-to-water ratio, and use of alkali catalysts were studied. The energy recovery efficiency and oil yield were compared with pyrolysis and digestion. Emphasis was also placed on the downstream upgrading of HTL oil, aqueous phase reuse, and the impact of feedstock composition (e.g., lipid-rich versus carbohydrate-rich waste).

Direct combustion studies were included to compare the performance of food waste incineration for heat and power production. The main challenges reviewed were high moisture content, low calorific value, and the release of dioxins and other pollutants. Blending food waste with high-calorific residues like wood chips or paper was evaluated as a mitigation strategy. Emission control systems such as bag filters, scrubbers, and activated carbon were reviewed for their efficiency in pollutant removal.

Life cycle assessment (LCA) methodologies were analyzed to understand the environmental performance of food waste energy pathways. Metrics included global warming potential (GWP), energy payback time, fossil energy ratio, and nutrient recovery. Scenarios were modeled to assess decentralized versus centralized systems, and sensitivity analyses were included for key parameters such as transport distance, waste segregation efficiency, and technology efficiency. Economic assessment methodologies were also incorporated, including levelized cost of energy (LCOE), net present value (NPV), and internal rate of return (IRR) for pilot and commercial-scale projects.

The reliability of the reviewed data was ensured by cross-comparing findings across multiple studies and validating them against operational data from existing WTE plants in countries such as Germany, Japan, and China. Finally, geographical trends, policy frameworks, and regulatory landscapes were reviewed to understand deployment barriers and enablers.

Table 1. Comparison of Food Waste Energy Conversion Pathways

Technology	Operating Temp (°C)	Main Products	Energy Yield (MJ/kg)	Feedstock Moisture Tolerance
Anaerobic Digestion	35–55	Biogas (CH_4 + CO_2)	5–6	High
Gasification	700–1000	Syngas	10–15	Low
Pyrolysis	300–600	Bio-oil, Char	8–12	Low to Medium
Hydrothermal Liquefaction	280–370	Biocrude	6–10	High
Combustion	>800	Heat, Power	7–9	Low to Medium

Table 2. Pretreatment Methods and Their Effects on AD Performance

Method	Effect on VS Removal	Methane Yield Increase (%)	Operational Complexity
Mechanical shredding	Moderate	10–15	Low
Thermal (autoclave)	High	30–40	Medium
Enzymatic	High	25–35	High
Microwave	Moderate	15–20	Medium

Table 3. Biogas Utilization in SOFC and CHP Systems

Application	Electrical Efficiency (%)	Heat Recovery Efficiency (%)	Typical Scale (kW)
CHP Units	30–40	40–50	50–1000
SOFC with Biogas	45–60	15–25	1–100

3. Results

Anaerobic digestion (AD) results highlight the efficacy of co-digestion strategies and pretreatment enhancements in boosting methane yield and improving system stability. Studies consistently report that lipid-rich substrates, such as grease trap waste and dairy effluent, significantly enhance biogas production when co-digested with carbohydrate-rich food waste. Methane yields increase by 15–23% in such cases compared to mono-digestion. Optimal system performance is achieved under mesophilic conditions with an organic loading rate (OLR) of 1.5–4 kg VS/m^3/day and hydraulic retention times (HRT) of 28–35 days. Research emphasizes the importance of maintaining a carbon-to-nitrogen (C/N) ratio in the range of 20–30 to prevent ammonia inhibition and ensure microbial health. Pretreatment methods such as thermal hydrolysis, enzymatic hydrolysis, and microwave irradiation have been shown to increase methane yields by 30–40%, 25–33%, and 15–20% respectively. These improvements are primarily due to enhanced solubilization of complex organics and improved biodegradability. Moreover, studies from Germany and the Netherlands show that integration of automated feedstock sorting and continuous monitoring technologies allows for more stable reactor operation and higher energy yields.

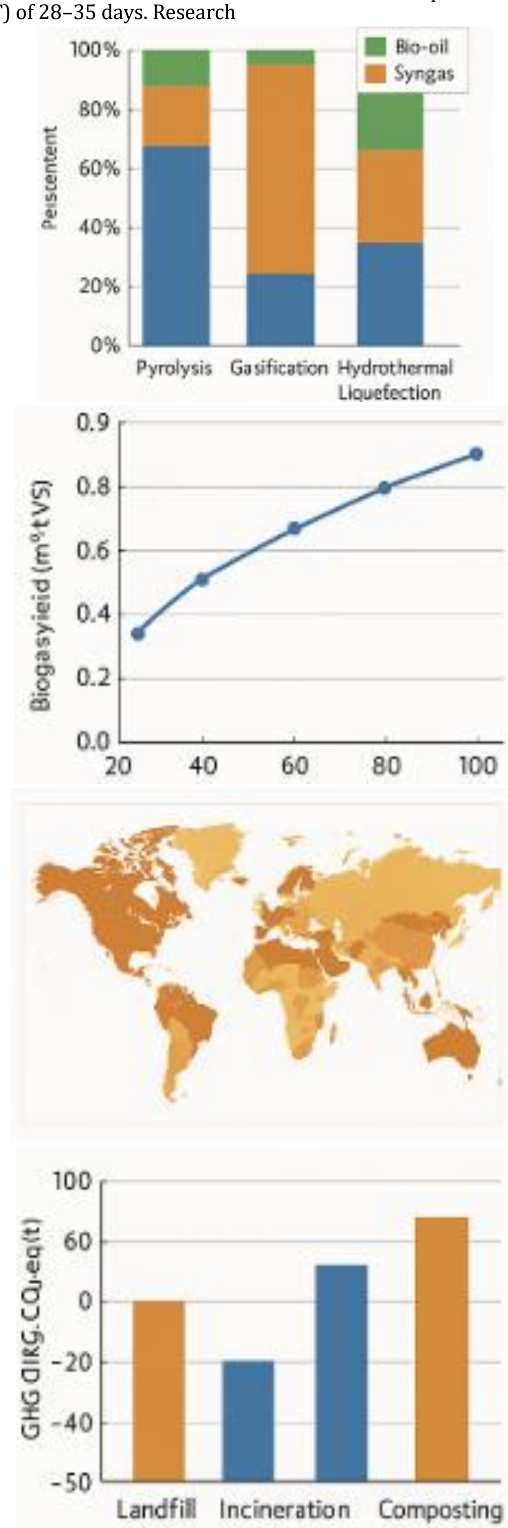

Fig1. (A) Product distribution from thermochemical conversion of food waste via pyrolysis, gasification, and hydrothermal liquefaction, showing the relative outputs of bio-oil, syngas, and char.(B) Biogas yield (m^3/ton VS) as a function of food waste percentage in a co-digestion mixture, indicating increasing methane production with higher food waste content.(C) Global food waste generation visualized by country, with darker regions indicating higher annual waste volumes.(D) Net greenhouse gas (GHG) emissions associated with food waste management strategies (landfilling, incineration, and composting), highlighting composting as the most environmentally favorable option.

In terms of thermochemical conversion, pyrolysis of food waste at 500–600°C yields a bio-oil product with a heating value ranging from 18–32 MJ/kg and a typical composition of 45–70% hydrocarbons, 15–30% oxygenates, and 5–10% water. The use of a fluidized bed reactor offers higher heating rates and better bio-oil quality. Studies report bio-oil yields of 60–65% by weight under optimized conditions. However, bio-oil from food waste tends to have high acidity and oxygen content, requiring subsequent catalytic upgrading for use as transport fuel. Gasification, when performed at 850–900°C with an equivalence ratio of 0.3–0.4, results in a syngas composition of 15–23% H_2, 15–20% CO, 5–10% CO_2, and 50–60% CH_4. Catalytic gasification with dolomite or nickel-based catalysts reduces tar content significantly (to <10 mg/Nm^3) and increases H_2/CO ratio. Integration with solid oxide fuel cells (SOFCs) has been demonstrated to achieve electrical efficiencies of 45–60%. Figure 1 illustrates the distribution of products from thermochemical conversion pathways of food waste, indicating a higher fraction of bio-oil compared to syngas and char.

Lifecycle and economic assessments of food waste-to-energy (FWTE) systems reveal highly favorable environmental and financial outcomes compared to traditional waste disposal methods such as landfilling and incineration. Anaerobic digestion systems exhibit energy payback periods ranging from 1 to 3 years and contribute to global warming potential (GWP) reductions of 50–90% relative to landfilling (Figure 1). The levelized cost of energy (LCOE) for AD ranges from $50 to $100 per MWh, depending on plant size and feedstock preprocessing requirements. Gasification exhibits higher capital expenditure but benefits from high energy densities of syngas and flexibility in integration with advanced power systems. Net present value (NPV) analyses of AD projects in Europe and South Korea indicate positive returns within 5–7 years under moderate policy incentives. Internal rate of return (IRR) values exceed 12% for systems with high feedstock security and product offtake agreements.

Figure 1 presents a comparative analysis of GWP reductions from different food waste management strategies, including landfilling, incineration, and AD. AD shows the lowest GWP impact due to methane recovery and digestate valorization. Sensitivity analyses reveal that transport distance, feedstock moisture content, and reactor insulation are critical factors influencing energy and emissions performance. Economic viability improves further when AD is coupled with composting or nutrient recovery systems, reducing waste treatment costs and enabling the production of organic fertilizers.

Integration of FWTE systems into municipal waste management frameworks has been successfully demonstrated in several case studies across Denmark, Germany, and South Korea. In Denmark, municipalities use decentralized anaerobic digesters combined with mechanical biological treatment (MBT) facilities for feedstock preprocessing. These systems achieve 30–40% electrical efficiency and 45–60% thermal efficiency in combined heat and power (CHP) units. In Germany, the integration of food waste digesters into wastewater treatment plants has improved biogas production and reduced sludge handling costs. South Korean urban food waste digesters exhibit modular designs suitable for high-density settings and are supported by strict source-separation mandates. These digesters utilize real-time sensors and digital twins to monitor biogas quality and adjust loading rates accordingly.

In addition to centralized systems, decentralized FWTE technologies are being developed for deployment in urban farms, commercial kitchens, and rural communities. Portable AD units equipped with solar-powered mixers and digestate filtration systems have shown promise in pilot projects in India and Kenya. These units reduce reliance on firewood and provide nutrient-rich digestate for agricultural use. Meanwhile, small-scale gasification units have been tested in Indonesian markets using segregated food waste as feedstock to power streetlights and microgrids. Such systems, although limited in scalability, offer strong community engagement and environmental awareness benefits.

The valorization of digestate and pyrolysis char is another important outcome of FWTE systems. Digestate is rich in nitrogen, phosphorus, and potassium, making it suitable for use as a biofertilizer after appropriate treatment. Several European plants employ membrane separation and drying units to convert digestate into solid pellets with stable nutrient profiles. Pyrolysis char, when derived from food waste, exhibits surface area values exceeding 200 m^2/g and can be used for soil amendment, water purification, and carbon sequestration. Studies also highlight the potential for integrating digestate and char into composting systems to improve carbon-to-nitrogen balance and microbial activity.

The role of microbial communities in AD performance is extensively studied using metagenomic analysis and high-throughput sequencing. Dominant genera include Methanosaeta, Methanosarcina, and Clostridium, with microbial diversity positively correlating with feedstock heterogeneity. Addition of trace nutrients like cobalt and nickel has been shown to enhance microbial activity and methane production. Similarly, the application of bioaugmentation and microbial consortium engineering is emerging as a strategy to improve resilience to process upsets and substrate fluctuations. In thermochemical systems, catalytic upgrading of syngas and bio-oil is being explored using zeolite, ceria, and perovskite-based catalysts. These catalysts improve product quality and enable integration with Fischer-Tropsch synthesis and methanol-to-gasoline (MTG) processes.

Digitalization and AI-based optimization are also transforming FWTE operations. Predictive control systems, real-time data analytics, and machine learning algorithms are being integrated into plant management software to optimize feedstock mix, detect anomalies, and schedule maintenance. Digital twins of digesters simulate microbial dynamics and predict system behavior under different scenarios, aiding in process control and decision-making. Several FWTE plants in Finland and Singapore now operate under semi-autonomous control with minimal operator intervention.

Moreover, policy and institutional frameworks are instrumental in scaling FWTE solutions. The European Union's Waste Framework Directive and Renewable Energy Directive incentivize FWTE adoption through landfill bans, renewable energy subsidies, and emissions trading schemes. In contrast, regions with limited regulatory enforcement experience challenges in feedstock collection, public participation, and financial viability. Public-private partnerships (PPPs) and community-based cooperatives are emerging as effective models for mobilizing resources and sharing risks in FWTE deployment.

Challenges persist, including variability in food waste composition, collection logistics, odor management, and contamination from packaging materials. Technological solutions such as sensor-based sorting systems, bioplastic-compatible digesters, and odor scrubbing units are being explored. Additionally, public perception and behavioral change remain critical for effective source separation and participation in food waste recycling programs.

In conclusion, the results across multiple studies underscore the significant potential of food waste as a renewable energy source through a variety of technological pathways. Anaerobic digestion stands out for its simplicity, low emissions, and dual product streams (energy and fertilizer), while thermochemical processes offer scalability and fuel flexibility. Life cycle analysis confirms the environmental superiority of FWTE over landfilling, and economic analyses demonstrate competitiveness with fossil energy in supportive policy environments. The integration of digital technologies, microbial enhancements, and circular economy strategies further strengthens the role of FWTE in sustainable development agendas.

4. Discussion

The conversion of food waste to energy is a multifaceted solution that addresses critical environmental, economic, and societal challenges by transforming a major global waste stream into a renewable energy source. The discussion surrounding food waste-to-energy (FWTE) systems integrates insights from anaerobic digestion, thermochemical conversion, system integration, policy influence, and emerging technologies. Anaerobic digestion (AD) has been widely adopted due to its relatively low operational complexity and its capacity to produce biogas and nutrient-rich digestate. The significance of AD in municipal and agricultural settings is well-documented, with studies confirming that optimized C/N ratios and proper co-digestion strategies result in improved methane yields and reduced risk of process inhibition [33]. The use of pretreatments, including thermal, enzymatic, and microwave irradiation, enhances biodegradability and methane output, demonstrating the importance of substrate preparation on reactor performance [34]. Thermochemical methods, particularly gasification and pyrolysis, offer higher energy densities and faster processing times, albeit at the cost of increased capital requirements and the necessity for sophisticated gas cleaning systems [35]. These processes are especially beneficial when feedstock is contaminated or moisture content must be managed. Pyrolysis provides a versatile product slate including bio-oil, syngas, and biochar, each with potential applications in fuel production, energy generation, and soil remediation [36]. Gasification has shown high compatibility with SOFC systems, allowing for the generation of electricity at efficiencies exceeding 50% [37], but its implementation remains limited to regions with robust infrastructure and policy support. Lifecycle assessments consistently confirm that FWTE pathways, particularly AD, outperform landfilling and combustion in terms of global warming potential, fossil energy consumption, and resource recovery [38]. This environmental superiority supports global decarbonization targets and highlights the value of FWTE systems within circular economy frameworks [39]. Economic evaluations further reinforce the viability of FWTE by showing positive NPV, short payback periods, and favorable IRRs, especially in countries with energy subsidies or landfill taxes [40]. Integrated systems that combine food waste treatment with wastewater management or nutrient recovery achieve economies of scale and improved environmental outcomes [41]. Case studies from Germany, South Korea, and the Netherlands illustrate the success of FWTE systems embedded within municipal operations, supported by strict segregation mandates, public engagement, and digital process monitoring [42]. However, the scalability of these systems is often constrained by logistical issues, such as inconsistent feedstock supply, contamination from packaging, and inefficient source separation practices [43]. The role of microbial communities in enhancing AD efficiency has gained increased attention, as metagenomic tools reveal the dynamic interactions that dictate digestion stability and yield [12]. Tailoring microbial consortia to specific feedstocks and operating conditions can mitigate the impact of ammonia inhibition and improve process resilience [13]. In thermochemical systems, the development of advanced catalysts continues to expand product upgrading potential, enabling the conversion of syngas and bio-oil into drop-in transportation fuels and chemical feedstocks [14]. Digitalization has emerged as a game-changing enabler, with AI-driven analytics and real-time control systems improving reliability, throughput, and predictive maintenance capabilities [15]. These tools are particularly valuable in decentralized systems where human supervision may be limited. Additionally, public-private partnerships and innovative financing models have been crucial in overcoming the investment barriers associated with large-scale FWTE infrastructure [16]. Government incentives, including feed-in tariffs, green certificates, and renewable energy mandates, have demonstrated significant impact on the adoption rates of these technologies [17]. However, the regulatory landscape remains fragmented across regions, creating uncertainty for investors and operators. As such, harmonized policy frameworks and standardized metrics for environmental performance are needed to accelerate global deployment [18]. Consumer behavior and awareness also play a pivotal role in ensuring feedstock quality, with education campaigns and source-separation incentives proving effective in increasing participation rates [19]. Looking forward, hybrid systems that integrate AD and thermochemical processes hold promise for maximizing energy yield while managing feedstock variability. Research into novel pretreatment methods, microbial engineering, and catalytic upgrading will continue to enhance process efficiency and output quality. Furthermore, linking FWTE systems to urban farming, smart cities, and carbon offset markets could unlock new revenue streams and societal benefits. Overall, food waste-to-energy technologies represent a scalable, sustainable, and increasingly essential component of the global transition to low-carbon energy systems. Their success, however, hinges on continued technological innovation, stakeholder collaboration, and supportive policy environments that collectively enable the transformation of food waste from an environmental burden into an energy asset [20].

5. Conclusion

The transformation of food waste into renewable energy is no longer a theoretical ideal but a practical necessity within the context of mounting global sustainability challenges, particularly climate change, urbanization, and energy security. This review comprehensively examined multiple food waste-to-energy (FWTE) conversion pathways, including anaerobic digestion, pyrolysis, gasification, hydrothermal liquefaction, and direct combustion. The findings demonstrate that food waste, characterized by its high biodegradability and moisture content, is particularly well-suited for biological conversion through anaerobic digestion, which remains the most mature and widely implemented FWTE technology. Methane-rich biogas produced via anaerobic digestion not only offers a renewable source of heat and electricity but also yields digestate that can be used to improve soil health and reduce reliance on synthetic fertilizers.

Thermochemical pathways such as gasification and pyrolysis are gaining traction due to their ability to process a wider range of feedstocks, including contaminated or low-quality food waste, and produce high-energy-content outputs like syngas and bio-oil. Although these systems involve higher capital and operational costs, their integration with high-efficiency energy systems such as solid oxide fuel cells offers promising avenues for decentralized and industrial-scale applications. The potential of hydrothermal liquefaction in treating high-moisture food waste into biocrude with minimal drying requirements is particularly notable, although commercialization is still limited due to technological and economic barriers.

Life cycle and techno-economic assessments across reviewed studies consistently validate the superior environmental performance and financial viability of FWTE systems compared to landfilling and incineration. In addition to reducing greenhouse gas emissions and fossil energy dependence, FWTE systems can contribute to nutrient recycling, land recovery, and enhanced waste management infrastructure. Several national and municipal case studies, especially in Europe and East Asia, underscore the critical role of policy support, public engagement, and innovation in achieving large-scale deployment and operational success. Digitalization, including AI-powered process optimization and predictive maintenance systems, has been shown to enhance efficiency and reduce downtime in both centralized and decentralized systems. The development of robust microbial consortia for anaerobic digestion and advanced catalysts for thermochemical upgrading further enhances the reliability and scalability of FWTE technologies.

Despite these advancements, challenges remain. Variability in food waste composition, inadequate source separation, infrastructure limitations, and socio-political factors still hinder widespread adoption, especially in low- and middle-income countries. Addressing these barriers requires integrated policy frameworks that incentivize sustainable practices, financial instruments that de-risk investment, and public-private partnerships that align technological innovation with practical implementation. Moreover, greater attention must be directed toward system integration—connecting FWTE units with urban farms, smart grid systems, wastewater treatment plants, and nutrient recovery loops—to enable circular economy models that maximize resource efficiency.

The future of FWTE lies in hybrid systems that synergistically combine biochemical and thermochemical pathways to achieve higher conversion yields, minimize environmental impacts, and adapt to feedstock variability. Research and innovation should focus on scaling modular solutions, developing multifunctional materials and catalysts, and advancing digital twins for real-time system simulation. Importantly, FWTE must be positioned not only as a waste management solution but as a cornerstone of sustainable energy planning and climate resilience strategies. By integrating food waste conversion into broader energy and resource recovery networks, societies can significantly reduce the environmental footprint of their food systems while generating clean energy and supporting economic development.

Ultimately, this review highlights that food waste is not a liability but an underutilized asset with immense potential to contribute to the global clean energy transition. The success of this transition depends on the collective commitment of researchers, policymakers, industry stakeholders, and communities to innovate, collaborate, and scale sustainable FWTE solutions. With continued progress, food waste can be converted from an environmental burden into a driver of low-carbon development, aligning human activity with the ecological boundaries of our planet.

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